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The influence of shock-pad density and footwear cushioning on heel impact and forefoot loading during running and turning movements

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Abstract: This investigation explored how shock-pad density and footwear cushioning influences soccer players' biomechanics. Ten participants (20.9 ± 2.5 yrs, 83.2 ± 7.1 kg, UK footwear size 10–11) wore three footwear cushioning conditions (soccer boot, soccer boot with cushioning insole and soccer boot with heel insert). Each footwear condition was tested on two shock-pad densities (55 g/litre and 65 g/litre) beneath a third generation carpet. For each footwear-shock-pad combination, eight running trials (3.81 m/s) and eight turning trials (consistent self-selected speeds) were collected. Pressure insole data were collected to provide a measure of player loading at impact and propulsion. Repeated measures ANOVAs demonstrated no main effects of footwear. The greater surface density did however, significantly increase ($p < 0.05$) measurements associated with loading during running (first metatarsal peak pressure) and turning (peak impact force, lateral heel and first metatarsal peak pressure). These findings suggest that shock-pad density is important in the regulation of player loading.

Keywords: force; pressure; soccer; shock-pad; cushioning; surface.

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1 Introduction

Whilst soccer is traditionally played on natural turf, third generation artificial surfaces are becoming increasingly used by both professional and amateur players. There has been an increased focus in the literature on the cushioning provided by these playing surfaces since an association has been made between increased surface cushioning and reduced risk of overuse injury (Arendt and Dick, 1995; Wong and Hong, 2005; Woods et al., 2002).

Many artificial playing surfaces are constructed with a shock-pad placed beneath the playing surface carpet. These shock-pads can be made from varying materials and with different densities to alter the levels of cushioning experienced by the performer (McNitt et al., 2004). To quantify the cushioning characteristics of a playing surface, various mechanical tests have been used. However, despite this being a useful way of ranking playing surfaces (Young and Fleming, 2007) it has been suggested that mechanical tests do not simulate player interactions well, often failing to demonstrate the same cushioning response that is observed during dynamic sport-specific human movement (Dixon and Stiles, 2003; Stiles et al., 2011). This therefore brings into question the suitability of mechanical tests to assess surface properties (Young and Fleming, 2007; Young et al., 2006). Additional biomechanical data is therefore also required to fully characterise the cushioning performance of a playing surface and to also understand the mechanism behind soccer player injury.

One possible mechanism behind overuse injury in soccer is that progressive forces are applied to the performer, overloading and eventually damaging the structures of the lower extremity (Nigg et al., 1995). Whilst direct measurement of these forces is difficult, ground reaction force data have been reliably used to indicate the magnitude and frequency of force transients produced during contact between the foot and the ground (Bobbert et al., 1992; Lieberman et al., 2010; Milner et al., 2006; Pohl et al., 2009). Greater peak ground reaction force has been associated with greater risk of overuse injury (Hreljac, 2004; Hreljac et al., 2000) and therefore, increased mechanical cushioning has been thought to lower these measurements (Low and Dixon, 2014; Stiles and Dixon, 2006).

In recent years there has been evidence to suggest that the occurrence of overuse injury may not relate to the overall magnitude of force but to the distribution and the magnitude of force at specific foot locations (Bus et al., 2004; Wang et al., 2012; Willems et al., 2005). In soccer, it may be appropriate to study this regional load at locations such as the medial and lateral heel and across the forefoot, as these are typically the position of the cleats on soccer boots. Regional force measurements at the heel and metatarsals have been shown to differ between playing surfaces of contrasting cushioning (Dixon et al., 2008; Ford et al., 2006; Girard et al., 2007; Low and Dixon, 2014) offering greater sensitivity to differences in cushioning than the measurement of peak impact force (Dixon et al., 2008; Low and Dixon, 2014). However, despite uniform cushioning being applied across the plantar foot, various studies have shown differences in regional load at some locations and not others (Dixon et al., 2008; Ford et al., 2006; Low and Dixon, 2014). This indicates the importance of measuring load at a range of plantar foot locations.

In soccer as well as other sports which utilise artificial playing surfaces, movements are dynamic and multidirectional which, as well as steady-state running, may contribute to progressive overloading of the player. Performing such movements has been shown to influence the ability of biomechanical measurements to detect differences between surfaces (Coyles et al., 1998; Queen et al., 2008; Stiles and Dixon, 2006). As such, to gain insight into the effect of a playing surface on the performer, consideration of these different movements may be supportive. Further still, the response of the player to the playing surface cushioning is complex and Dixon et al. (2008) identified that the response to the surface is also influenced by the footwear that is worn. Full length cushioning insoles and visco-elastic heel inserts have been shown to reduce lower extremity pain (Faunø et al., 1993; Gardener et al., 1988; MacLellan, 1984). These are used in soccer to add cushioning to the footwear and therefore should also influence the loading of players during dynamic movements on different shock pad densities.

The present investigation explores the cushioning a player receives by measuring selected biomechanical variables on different shock-pad densities. The paper also aims to identify how the footwear worn and the movements performed influence the ability to determine differences in surface cushioning. It was hypothesised that with decreased shock-pad density, cushioning will be greater which will be represented by reduced lower extremity loading at impact (impact force) and propulsion (peak propulsive force). It was also hypothesised that peak pressure at the medial and lateral heel and at the first and fifth metatarsal will be significantly reduced on a lower shock pad density. Lastly, it was hypothesised that an interaction between shock-pad and footwear condition will exist where reduced loads will be experienced on the less dense shock-pad in more cushioned footwear.

2 Methods

Ten male amateur soccer players (20.9 ± 2.5 yrs, 83.2 ± 7.1 kg, UK footwear size 10–11) volunteered as participants in this study (ethically approved by the institutional ethics procedure at the University of Exeter). Participants wore three footwear conditions: rubber cleated soccer boot (Copa Mundial, Adidas); soccer boot with a 10 mm heel insert (Sorbothane Shock Stopper heel pads, Sorbo products, Lancashire, UK); and soccer boot with a full-length cushioning insole (ProSole, Sorbo products division, Lancashire, UK).

Each footwear condition was tested on two different shock-pads (Brock Performance F24, Arpro® Expanded polypropylene BF2455W, Brock International, Colorado, USA), one of which had a density of 55 g/litre and the other 65 g/litre (thickness of 24 mm ± 0.5 mm). These were positioned on 15 metres of concrete flooring and had a third generation carpet placed on top (Astroplay MXS 40, Lano sports, Herelbeke, Belgium). The carpet was constructed of artificial grass made up of 40 mm polyethylene monofilament yarn. Upon this carpet, a mixture of 10 kg/m^2 of sand and 8 kg/m^2 of rubber crumb were added, as recommended by the manufacturer. This was brushed so it was uniformly distributed.

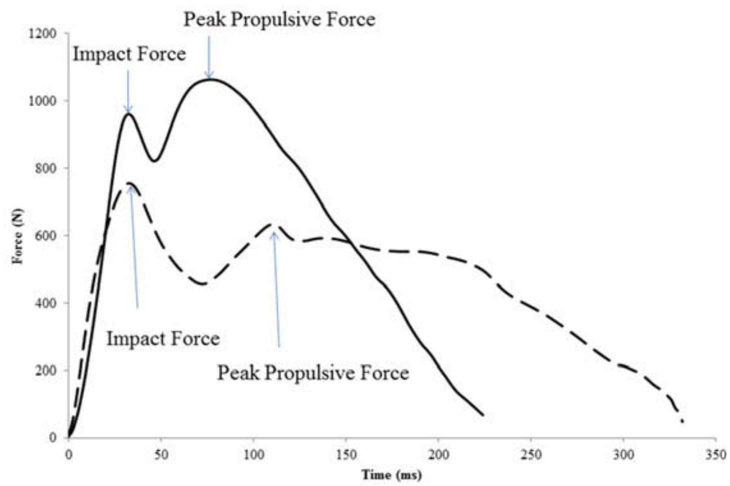
The shock-pad densities were mechanically compared using a hybrid method developed by Carré et al. (2006). A mass-spring-damper model of a deformable ball impacting on a rigid surface was combined with a model of a rigid hammer-surface impact to form a model with two degree-of-freedom. The test apparatus included an impact hammer (2.1 kg) with a pre-calibrated accelerometer contained within a hemispherical hammer profile (62 mm diameter). The hammer was dropped from a height of 15 cm on to the shock-pad (without the carpet) and at contact the voltage signal from the accelerometer was used to calculate the force throughout the impact phase (Carré et al., 2006); this was performed at ten random locations. The peak force (N) was taken as a measure of the maximum deceleration of the hammer during impact, where higher impact decelerations suggest a harder surface. The mean average and standard deviation for this measure was calculated for both shock-pads. Additionally, surface cushioning was measured with a standard 0.5 kg Clegg hammer (Model 500GT, Dr Baden Clegg Pty Ltd, Australia). The test required a rigid mass with an accelerometer attached to be dropped through a tube 30 cm in height onto each surface. Hardware attached to the accelerometer sampled the acceleration and displayed the peak value of deceleration during impact in acceleration due to gravity (g's) (Carré et al., 2006). The test required four preliminary drops in the same location and on the 5th drop the value was used to indicate the level of surface cushioning (Dr Baden Clegg Pty Ltd, Australia). Drops were performed directly onto each pad at five random locations.

Each participant performed 16 trials for each of the six different surface-footwear combinations (8 running [3.83 m/s] and 8 turning [a consistent self-selected speed, average 3.52 m/s ± 0.12 m/s]). For both the running and turning tasks, participants used 5 m to run up to a square marked on the turf (0.5 m × 0.5 m). With their right foot, they contacted within this area. For the running task, participants then continued along the length of turf. Running speeds were controlled using photo sensitive timing gates (Brower timing systems, Utah, USA) placed either side of this marked area. For the turning movement, participants placed their right foot flat inside the square area, turned and pushed off at the same speed and direction to which they came. Timing gates were used to assess the time between entry onto and exit from the marked area. For both tasks, the data from the step made within the area was used for analysis as this ensured the participants' data were collected at the standardised location and speed. Any running or turning trial not at the selected speed (± 5%) or in the specified style (visually monitored) was repeated.

3 Data analysis

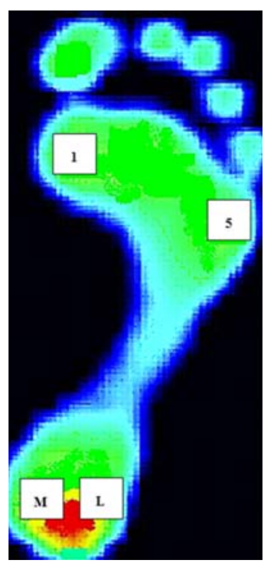
Each footwear-surface combination was tested in a counterbalanced order in a 3 × 2 repeated measures design. In-shoe pressure data were collected with footscan pressure insoles (RSscan International, Belgium, 500 Hz, size 10 and 11), placed within the footwear above the cushioning insole and insert. Data were then collected via a data logger worn by the participants and then transferred to a computer after the completion of the trial for later analysis. This meant that there was approximately 1.5 minutes recovery between each trail. These data collected during running and turning included peak impact and propulsive forces (Figure 1).

Figure 1 Example of typical force-time histories for running (solid line) and turning (dashed line) (see online version for colours)



Note: The location of peak impact force and peak propulsive forces are identified for each movement.

Figure 2 Location of masks used to determine peak pressure at the medial (M) and lateral (L) heel and first (1) and fifth (5) metatarsals (see online version for colours)



The pressure insole also provided peak pressure data at the medial and lateral heel and at the first and fifth metatarsal areas (Figure 2). The Footscan insoles have been shown to provide reliable data ensuring confidence in the data comparison, although values have been shown to be lower in magnitude than those collected by a force plate (Low and Dixon, 2010). To adjust the magnitude of force measured, a custom method of calibration was used whereby the insole values were adjusted by the difference between the participant's body weight, measured using a set of standard weighing scales, and values measured by the insole during a single leg standing task. This was performed for each footwear-surface combination.

Significant differences were identified using a two-way (shoe × surface) ANOVA with repeated measures ($p < 0.05$) for each dependent variable. The statistical package SPSS (Version 17, SPSS Inc, Chicago, USA) was utilised for this analysis. Post-hoc paired samples t-tests with Bonferroni corrections were used to identify the location of significant differences. Partial eta squared effect sizes (η^2_p) were calculated for the main effects of each two-way ANOVA with repeated measures. Small, moderate and large effects were represented by values of 0.01, 0.06 and 0.14 respectively (Gray and Kinnear, 2012). Mechanical cushioning values were compared using Cohen's d effect size interpretation of 0.8, 0.5 and 0.2 for large, moderate and small effects respectively (Cohen, 1988).

4 Results

Using the mechanical test presented by Carré et al. (2006), the denser shock-pad (65 g/litre) had greater peak forces (1,254.3 ± 48.5 N) compared to the less dense shock-pad (1,238.5 ± 46.1 N). Based on Cohen's d criterion values, a small effect size (d = 0.33) was identified for differences in force between the shock-pad. The Clegg hammer test revealed that the average hardness for the surface was reported as 108.0 g (± 3.1) for the more dense shock-pad and 99.9 g (± 12.5) for the less dense shock-pad. The difference between the surfaces represented a large Cohen's d effect size (d = 0.89).

For the running movement (Table 1), significant main effects were shown for surface density where the statistical analysis indicated that regardless of the footwear worn, first metatarsal peak pressure was reduced on the less dense shock-pad condition ($p = 0.03$, $\eta^2_p = 0.42$). No other significant main effects were observed for peak impact ($p = 0.11$, $\eta^2_p = 0.26$) and propulsive force ($p = 0.40$, $\eta^2_p = 0.08$) or peak pressure at the medial ($p = 0.33$, $\eta^2_p = 0.10$) and lateral heel ($p = 0.44$, $\eta^2_p = 0.07$) or fifth metatarsal ($p = 0.57$, $\eta^2_p = 0.04$) during running. For the turning movement (Table 2), reduced peak impact forces ($p = 0.05$, $\eta^2_p = 0.49$) and peak pressures at the lateral heel ($p = 0.05$, $\eta^2_p = 0.45$) and first metatarsal ($p = 0.01$, $\eta^2_p = 0.43$) were experienced on the less dense shock-pad. No significant main effects were observed for peak propulsive force ($p = 0.30$, $\eta^2_p = 0.07$) and peak pressure at the medial heel ($p = 0.34$, $\eta^2_p = 0.13$) and fifth metatarsal ($p = 0.19$, $\eta^2_p = 0.23$). There were also no main effects of footwear for any measurement when running ($p > 0.05$, $\eta^2_p > 0.01 – 0.18$) and turning ($p > 0.05$, $\eta^2_p = 0.03 – 0.32$) independent of surface.

Table 1 Summary of force and pressure data collected whilst running

	55 g playing surface			*Surface average*	*65 g playing surface*			*Surface average*
	Control	*Heel insert*	*Insole*		*Control*	*Heel insert*	*Insole*	
	M ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*
Peak impact force (BW)	1.9 ± 0.4	1.8 ± 0.4	1.8 ± 0.3	1.8 ± 0.4	1.7 ± 0.3	1.8 ± 0.3	1.8 ± 0.3	1.8 ± 0.3
Peak propulsive force (BW)	1.8 ± 0.2	1.8 ± 0.2	1.8 ± 0.3	1.8 ± 0.2	1.9 ± 0.2	1.9 ± 0.2	1.9 ± 0.2	1.9 ± 0.2
Medial heel peak pressure (KPa)	390.4 ± 107.4	359.0 ± 107.4	418.8 ± 121.8	389.4 ± 112.2	404.8 ± 83.2	419.0 ± 128.4	401.2 ± 119.2	408.33 ± 110.3
Lateral heel peak pressure (KPa)	418.4 ± 181.2	363.2 ± 149.0	376.8 ± 126.0	386.1 ± 152.1	394.0 ± 82.8	404.4 ± 106.2	367.0 ± 82.6	388.5 ± 90.5
First metatarsal peak pressure (KPa)	265.8 ± 96.4	246.6 ± 68.8	257.0 ± 70.8	256.5 ± 78.7	275.0 ± 89.4	257.8 ± 126.0	263.2 ± 107.0	265.3 ± 107.5*
Fifth metatarsal peak pressure (KPa)	242.4 ± 171.0	215.8 ± 119.2	191.4 ± 53.8	216.5 114.7	194.5 ± 87.6	198.4 ± 53.0	186.2 ± 38.0	193.0 ± 59.5

Notes: M, mean; SD, standard deviation; BW, body weight; KPa, kilopascal. * denotes a statistical difference between surfaces ($p < 0.05$).

Table 2 Summary of force and pressure data collected whilst turning

	55 g playing surface			*Surface average*	*65 g playing surface*			*Surface average*
	Control	*Heel insert*	*Insole*		*Control*	*Heel insert*	*Insole*	
	M ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*
Peak impact force (BW)	1.8 ± 0.4	1.8 ± 0.3	1.8 ± 0.5	1.8 ± 0.4	2.4 ± 0.3	2.0 ± 0.3	2.0 ± 0.3	2.1 ± 0.3*
Peak propulsive force (BW)	2.6 ± 0.5	2.3 ± 0.3	2.4 ± 0.4	2.4 ± 0.4	2.4 ± 0.8	2.6 ± 0.6	2.2 ± 0.6	2.4 ± 0.7
Medial heel peak pressure (KPa)	779.4 ± 134.0	756.6 ± 207.8	696.4 ± 256.2	744.1 ± 168.1	829.0 ± 193.8	692.2 ± 95.8	725.4 ± 126.4	748.9 ± 138.7
Lateral heel peak pressure (KPa)	344.6 ± 165.0	302.8 ± 124.4	309.4 ± 162.6	318.9 ± 117.3	318.4 ± 125.8	318.8 ± 100.4	361.0 ± 125.8	332.7 ± 117.3*
First metatarsal peak pressure (KPa)	305.8 ± 71.6	255.6 ± 48.0	318.6 ± 66.8	293.0 ± 62.1	465.4 ± 308.2	452.0 ± 260.2	418.6 ± 212.6	445.3 ± 260.3*
Fifth metatarsal peak pressure (KPa)	95.2 ± 57.2	112.8 ± 43.4	89.2 ± 53.0	99.1 ± 51.2	124.2 ± 57.0	111.6 ± 45.2	139.6 ± 58.4	125.1 ± 53.5

Notes: M, mean; SD, standard deviation; BW, body weight; KPa, kilopascal. * denotes a statistical difference between surfaces ($p < 0.05$).

Table 1 and Table 2 also provide the interactions calculated between the footwear and surface conditions for the running and turning tasks performed by all participants. A significant interaction occurred for the measurement of peak impact force whilst turning. The post-hoc tests revealed that despite a trend towards greater forces for the soccer boot condition on the denser surface, no differences were found ($p > 0.05$, $\eta^2_p < 0.01 - 0.15$ for running and $\eta^2_p < 0.05 - 0.39$ for turning).

5 Discussion and implications

As the magnitude of cushioning provided to the soccer player has been associated with the risk of sustaining an injury (Arendt and Dick, 1995; Wong and Hong, 2005; Woods et al., 2002), the current investigation explored how two different shock-pad densities influence the loads experienced by the player. Due to the relationship between an increased magnitude of force and the greater susceptibility to injury, it was hypothesised that the denser shock-pad would provide less cushioning and result in greater force being experienced at impact and propulsion when running. Results however, did not support such hypothesis. Whilst this is contrary to the initial expectation, it does provide further support to similar literature on running where differences were not shown when using the impact force variable (Dixon and Stiles, 2003; Nigg and Yeadon, 1987). This supports previous suggestions that resultant force data is not sufficiently sensitive to detect changes in cushioning (Dixon et al., 2008) due to the measurements representing load from across the foot and not just the heel or forefoot (Shorten, 2002).

In contrast to total resultant force data, analysis of regional load at the first metatarsal area did indicate reduced loading on the less dense shock-pad, which suggests a redistributed load across the fore-foot during the propulsive phase (Dixon et al., 2008; Shorten, 2002). This supports the suggestion of the improved sensitivity with the use of regional load (Dixon et al., 2008) and also indicates the importance of pressure data when comparing playing surface cushioning.

Whilst there were a limited number of significant differences during steady-state running, the current investigation also demonstrated that in agreement with other investigations (Coyles et al., 1998; Low and Dixon, 2014; Queen et al., 2008; Stiles and Dixon, 2006), dynamic movements such as the turning action can influence the comparison of playing surfaces. In support of previous research (Low and Dixon, 2014; Stiles and Dixon, 2006), reduced peak impact forces were found on the less dense surface. Peak pressures at the lateral heel and the first metatarsal area were also smaller when turning on the more cushioned shock-pad which is also in agreement with previous research (Low and Dixon, 2014). These collective findings suggest that shock-pad density may become more important for dynamic movements such as sprinting, cutting and turning than for steady-state running. Further still, had the crumb rubber in the carpet top surface aged or the quantity reduced to replicate surface degradation, other significant differences for turning as well as steady-state running may have been shown. This suggestion is based on results of mechanical tests where the shock-pad has played an increased cushioning role when degradation of the top surface occurs (Fleming et al., 2008; McNitt et al., 2004).

The current investigation demonstrates the importance of biomechanical data to compare playing surfaces during both steady-state running and turning trials. Effect sizes magnitudes taken for the biomechanical comparisons are different to those obtained from the mechanical tests albeit the directions of the differences were in agreement. This supports the suggestion of Young and Fleming (2007) who identified that mechanical tests are a useful way of ranking surfaces whilst also highlighting that the tests used are not representative of the level of difference in playing surface cushioning experienced by the player.

In comparison to the work of Ford et al. (2006), the observation of peak pressure differences at the medial forefoot is contradictory to their study findings. One possible reason for this may be because the two studies did not calculate peak pressure in the same way. Ford et al. (2006) calculated peak pressure over a larger area compared to the current investigation which used smaller pressure masks. Consequently, using masks at locations where the cleats are approximately located seems to improve the sensitivity to detect differences in cushioning. Findings may also indicate the importance of the turning movement to observe differences where other movements such as cutting and running cannot.

The observed reduction in peak pressure at the medial forefoot may have implications regarding injury to the first ray (the combination of bones and joints that make up the medial boarder of the foot). According to Nihal et al. (2009), injury to the first ray is extremely common in soccer, and is possibly a result of high medial loading during dynamic soccer specific movements (Eils et al., 2004; Wong et al., 2007). Therefore, the evidence of reduced loading in this area suggests that using lower density shock-pads for match and practice surfaces may reduce the risk of common first metatarsal injury in soccer.

The statistical tests performed also computed the interactions between surface and footwear for the different dependent variables. There was a significant interaction between footwear and surface for the measurement of peak impact force, where it appeared that forces were greatest for the soccer boot condition on the denser surface. The relative importance of the footwear on players' response to playing surfaces has been previously discussed (Dixon et al., 2008). Despite this trend however, the individual paired samples t-tests were unable to reveal differences which given the large effect size, may relate to reduced statistical power obtained with the sample size used. This study limitation may also be true for certain variables when the surface and footwear were compared independently.

As well as influencing the comparison of the playing surface, the relative importance of footwear cushioning independent of the surface was measured. Sorbothane® reported numerous benefits for the use of their soccer specific cushioning insole including increased impact absorption. Impact and propulsive forces and peak pressures measured in the current investigation were however not significantly reduced with the full length insole compared to the soccer boot with no cushioning insole. Impact forces and peak pressure at the medial and lateral heel were also not significantly reduced with heel insert use. Whilst this is in contrast to much previous literature regarding cushioning insoles (Dixon et al., 2003; House et al., 2002), there are also examples in the literature of cushioning insoles not influencing force variables (Nigg et al., 1988). A key aspect in these comparisons is the characteristics of the shoe and surface. If the shoe-surface interface already provides adequate cushioning, then it has been suggested that a cushioning insole within the shoe is less likely to further reduce loads (Dixon et al., 2003). For example, the work of Nigg et al. (1988) utilised running shoes which already have a relatively large amount of cushioning, whilst the work of House et al. (2002) and Dixon et al. (2003) involved the use of military boots, providing limited cushioning. It is therefore suggested that the lack of significant influence of the cushioning insole or heel insert in the current study may be contributed to by the relatively high cushioning already being provided by the third generation artificial soccer surfaces used in this study.

In order to fully understand the impact of footwear and surface conditions on player loading during soccer, other movements such as sprinting, jumping and lateral cutting movement should be studied. The study also used a surface which was constructed as if it were new. Future study of the shock-pad densities would therefore benefit from degrading the surface materials so to improve understanding of the role of the infill on cushioning provided to the performer. Use of a greater range of pad density would also be of interest when trying to protect the performer from high loading during match play and training as well as potentially influencing the response of the performer to the in-shoe cushioning used in the current study.

Another study limitation may be that whilst the use of footscan pressure insoles is reliable and that there is confidence with the within-subject comparison, the insoles appear to have no appropriate calibration method and consequently have been shown to underestimate force and pressure data by approximately 50% (Low and Dixon, 2010). The custom approach used to calibrate the insoles used in this study allowed impact force values to be obtained that were approximately two times the participants' body weight. This is typical for force measured via a force plate whilst running at similar velocities (Dixon et al., 2000; Hreljac et al., 2000; Munro et al., 1987). Likewise, turning values were similar to those reported for this movement on natural turf (Stiles et al., 2011) and therefore there is confidence that force and pressure values are realistic for the conditions tested.

6 Conclusions

The results of the present investigation demonstrate that reducing the shock-pad density by 10 g/litre significantly decreased some force and pressure measurements associated with injury. As this was not true for all dependant variables, the study hypotheses can only be partially supported. Never-the-less, consideration should be given to the use of lower density shock-pads within third generation turf to help soccer players reduce injury risk. The study also highlighted the relative importance of type and location of measurement and the movement performed when using force and pressure measurement to detect differences in surface conditions. Lastly, the results showed that the footwear interventions had no effect on dependant variable measures when interacting with surface density.

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